TRA 21/22 Building and Programming a Quantum Computer

Automating Qubit Tune-up and Mixer Calibration

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Preface

This report is based on the work we did as a part of the Tracks course in Building and Programming quantum computer. Part of the work is continuation of the work done by previous students on the qubit calibration.

The authors would like to extend special thanks to our supervisors Axel Eriksson and Claudia Castillo Moreno for their help and the support during the project. Also we would like to thank Simone Gasparinetti and Attila Geresdi for the opportunity to work on this project through the course.

Abstract

In this project we write scripts to automate qubit tune-up and mixer calibration, with the aid of the Labber instrument software and the Labber Python API. The python scripts are written to perform the measurements on two microwave platforms, Vivace and Keysight. The scripts then process the data from the measurements to extract the desired measures for qubit tuneup and mixer calibration. To conclude we note that although the scripts are able to perform there is still much room for improvement.

Contents

1 Introduction

Qubit tuning is crucial within the field of quantum computing, especially in the stages of combining multiple qubits. It is very difficult to fabricate qubits of the exact same frequency and when working with multiple qubits in the same system the frequencies are often needed to match. A way to solve this is to make the qubits flux tunable in order to be able to regulate the frequencies. Furthermore, flux tunability also opens up the possibility to put the qubits in resonance. This enables them to swap their states with each other and they can then be tuned "away" from each other again to prevent further interaction.

To interact with and manipulate these qubits, more accurate control of the frequency, amplitude and phase of microwave signals is required. To allow for this level of modulation IQ mixers are commonly utilized. Mixer calibration is the process of minimizing signal leakages of an IQ mixer. When working with flux tunable qubits, the frequencies involved might change often as the flux is repeatedly tuned. This changes the optimality of the mixer calibration, and leads to an increased need for frequent recalibration.

In this report we detail or work in automating the qubit tuneup process described above as well as the mixer calibration process through Python scripts. We utilize Labber, a complete software solution for instrument control and lab automation, to interface with the many instruments necessary to perform the various necessary measurements. Labber also offers a comprehensive Python API which we use to create python scripts to automate the tuneup and mixer calibration processes. The full API is described in the Labber User Manual. Labber operates through measurement scenarios, which describe full measurements to execute on the available instruments. By pre-configuring scenarios in Labber and then modifying them through Python we are able to produce scripts to automate chains of experiments.[1]

Finally, we also aim for the scripts to operate on two different microwave platforms, Vivace by Intermodulation Products, and Keysight's range of wave generators. These platforms both interface well with Labber, although there are some differences in the names of channels and the operation of the different systems.

2 Theory and Method

2.1 Mixer Calibration

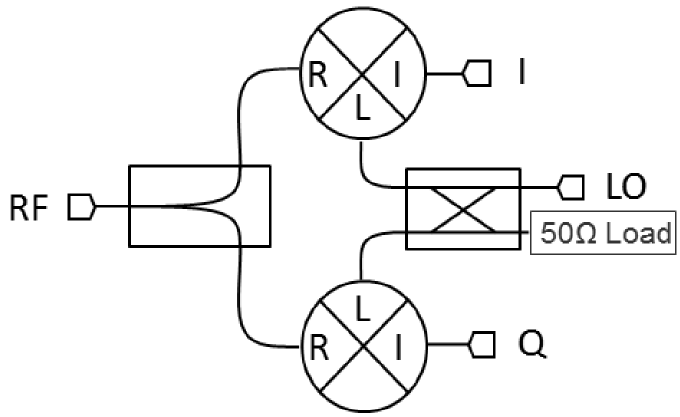


Figure 2.1: Example schematic of an IQ-mixer. Image sourced from [2].

To manipulate and measure qubits we require precise control over the frequency, amplitude and phase of microwave signals. To achieve this we use in-phase/quadrature (IQ) mixers. An IQ mixer consists of two microwave mixers, with the same local oscillator frequency with a 90°-phase shift between them. The intermediate frequency ports on each of the microwave mixers are called the in-phase (I) and quadrature (Q) ports respectively. See Figure 2.1 for a schematic of an IQ mixer.[3]

2.1.1. Single Sideband Upconversion

To achieve a RF signal of a desired frequency, it would be possible to simply produce a LO signal at the desired frequency and modulate it through DC currents applied to the I and Q ports. This is undesirable, however, mainly since any realized IQ mixer exhibit a leakage of the LO signal at the RF port, even if no signal is applied to I and Q. This could result in the transmission of a signal at the target frequency when it is not desired.

To avoid this, single sideband upconversion is instead used to produce a RF signal. This is done by applying a continuous wave carrier signal to the LO port,

$$s_{LO}(t) = \cos(\omega_{LO} t),$$

and then applying an intermediate frequency (IF) signal with the same amplitude to the I and Q ports, in phase quadrature:

$$s_I(t) = A_{IF} \cos(\omega_{IF} t),$$
$$s_Q(t) = A_{IF} \cos(\omega_{IF} t + \frac{\pi}{2}).$$

This theoretically outputs a RF signal with a single frequency, which is the sum of the LO and IF frequencies,

$$s_{RF}(t) = \frac{1}{2} A_{IF} \cos((\omega_{LO} + \omega_{IF})t).$$

The term single sideband refers to the fact that a general mixing of this kind would result in two frequency bands, $f_{LO} + f_{IF}$ and $f_{LO} - f_{IF}$. By having equal amplitude and phase quadrature on the I and Q ports one of these sidebands are cancelled, assuming an ideal IQ mixer.[3]

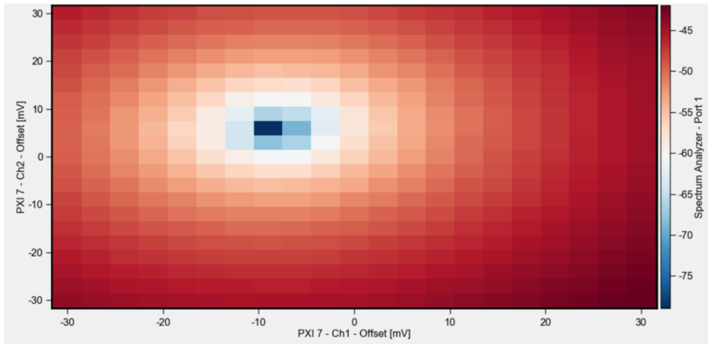


Figure 2.2: Plot of the LO leakage as a function of the voltage offsets of the I and Q ports. We seek to find the minimum when calibrating the LO leakage.

2.1.2. IQ Mixer Imperfections

As mentioned previously, IQ mixers typically exhibit a leakage of the LO signal at the RF port. This is usually the result of different conversion losses in the two RF mixers used in the construction of the IQ mixer. The LO leakage can therefore be minimized by slightly offsetting the voltage of the I and Q ports by some optimal value.

Another imperfection is an imbalance of amplitude and phase between the two RF mixers. This leads to a weaker than desired cancellation of the unwanted sideband during upconversion, but this can be diminished by slightly changing the phase and amplitude on one of the I or Q ports until we see a minimal leakage of the unwanted sideband.[3]

2.1.3. Automating Mixer Calibration

Based on the imperfections mentioned in 2.1.2., we want to calibrate a mixer to minimize both the LO and sideband leakage. To do this we utilize a spectrum analyzer, as well as wave generators for the LO and IF that interfaces with the Labber software and allows fine control of the frequency, phase and amplitude of their signals.

Minimizing the LO leakage can then be done through Labber with a single experiment, which sweeps the voltage offset of the I and Q ports respectively and, using Labber's built-in optimization capabilities, find the optimal values for these offsets. An example of the space over which this optimization takes place can be seen in Figure 2.2. This gives us an optimal voltage offset for each port.

With these optimal voltages obtained we can then proceed with sideband calibration, which can be done very similarly to the LO leakage. Here we use Labber's built in optimizer to instead optimize over the amplitude scale and phase of the signal to either the I or Q port, with the port voltage offsets set to the acquired optimal offsets. This then produces optimal values for the amplitude ratio and phase between the two ports as well. These values allow the mixer to work optimally to produce values at the desired frequency, with as little leakage as possible.

It is worth noting that these calibration values might vary as the LO and IF frequencies change. Thus mixer calibration must be done regularly, especially when changing frequencies, to guarantee that the mixer perform optimally.

2.2 Spectroscopy

Two kinds of spectroscopy are used. The resonator spectroscopy is to find the resonator frequency, which in turn is needed in the two-tone spectroscopy used to obtain the qubit frequency. This part of the project is a continuation of previous work done by students. We have used their work as a base and modified and also expanded their script in order for it to better fill its purpose.

2.2.1. Resonator Spectroscopy

In resonator spectroscopy a resonator drive sends pulses of different frequencies that pass by the resonator and are collected and measured. At a certain frequency the resonator will start to resonate, thus reflecting some of the signals back. This gives rise to a dip in the produced spectrum at this certain frequency as seen in figure 2.3 and the resonator frequency is found.

This particular frequency is then used to obtain the qubit frequency. An excited qubit will cause a shift in the resonator frequency due to a phenomenon called "dispersive coupling" where the qubit and the resonator interact with each other. This shift is then utilised to decide whether the qubit is excited or not which is crucial for the next step of the analysis.[4]

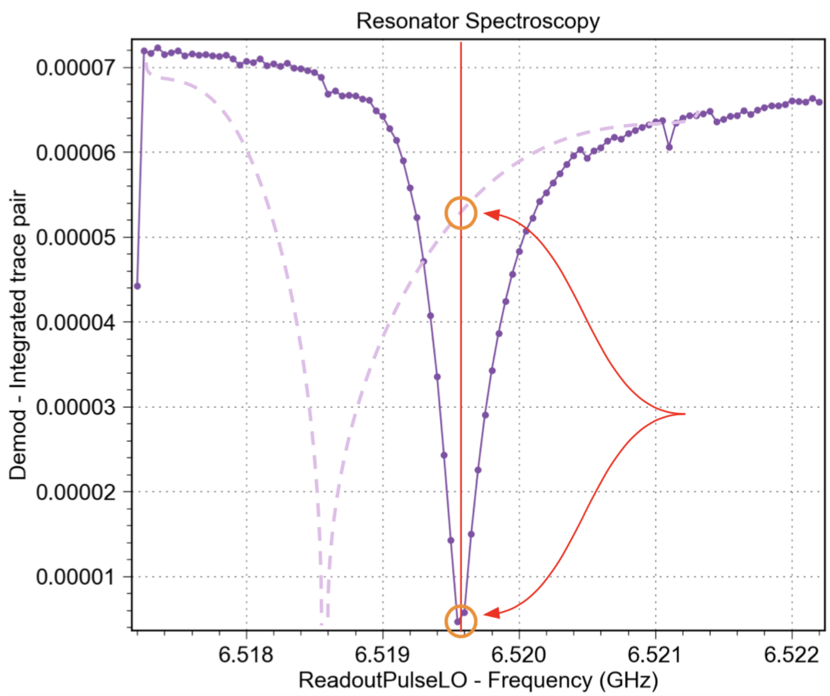


Figure 2.3: Example of a spectrum produced by resonator spectroscopy with a dip showcasing the resonator frequency. A possible spectrum after dispersive coupling occurs is shown as a dotted line. The first point in the spectrum is likely a remain from a previous measurement due to a bug in the software and should not be paid attention to.

2.2.2. Two-Tone Spectroscopy

The frequency obtained in the resonator spectroscopy is used as a base for the two-tone spectroscopy. By measuring the signal at this frequency it is possible to deduce whether the qubit is excited or not. A system with a qubit in the ground state would give a signal corresponding to the bottom of the dip in the spectrum, see the lower circle in figure 2.3, while measuring the same frequency while the qubit is excited would return a signal corresponding to the top circle in figure 2.3

due to the shift from dispersive coupling.

When performing two-tone spectroscopy an approximate qubit frequency calculated elsewhere is used to sweep around in order to save time. Long pulses of at least three times the qubits relaxation time are used. These long pulses will at the right frequency measure whats called a “mixed state” meaning that during the duration of the pulse the qubit will be measured in both the ground state and the excited state and the output value will be an average of the two, seen in figure 2.4. It is thus possible to find the frequency that excites the qubit and causes the dispersive coupling. The last step is to recalculate the sweep steps into that frequency which is done with equation 2.2.2. [4]

$$qubitLOfreq - sweeplinearcenter + \frac{sweeplinearspan}{2} - sweeplinearspan \cdot \frac{maxfreq}{nsteps - 1} \tag{2.2.2}$$

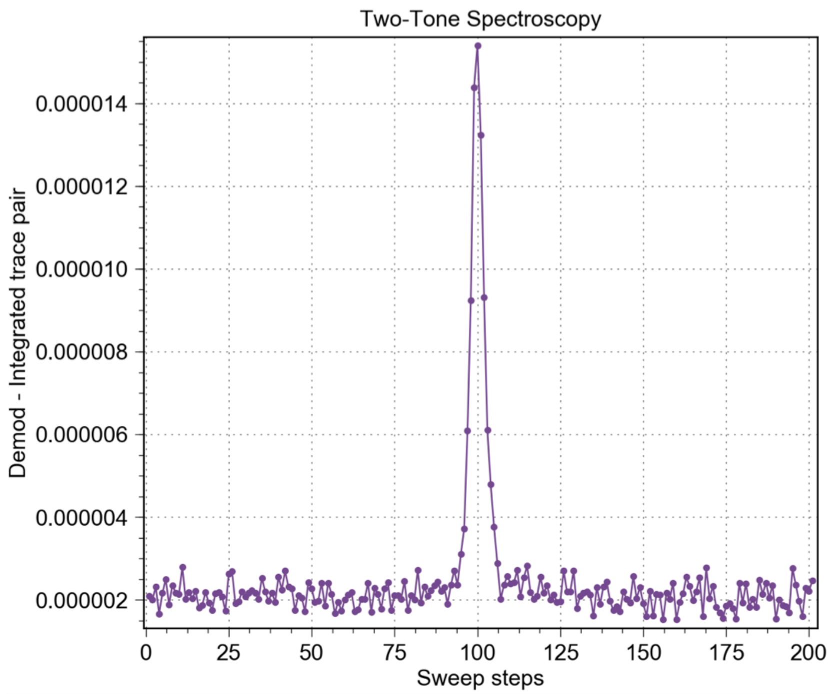


Figure 2.4: Example of a spectrum produced by two-tone spectroscopy with a peak showcasing the qubit frequency in terms of steps. The y-axis is later recalulated into giga Hertz.

2.3 Rabi-Ramsey

The Rabi-Ramsey experiments are the time domain experiments. These experiments require preparation, manipulation and readout of the qubits. Through these experiments the qubit characteristics can be found.

2.3.1. Rabi Measurements

In Rabi experiment the π pulse amplitude of the qubit is calculated, which is the amplitude voltage at which the qubit reaches excited state from the ground state. This is how it is achieved, first a qubit is created in a ground state, then a sweep over the amplitude of the input qubit signal is conducted to find the voltage amplitude at which the qubit reaches the excited state [3] [5].

2.3.2. T_1 Measurement

In T1 qubit decay time is calculated, which is achieved as follows, first the qubit is created in excited state, by sending the π-pulse to the qubit, then after t the qubit the measured again to observe it's state, this experiment is performed many times to obtain the T_1, which is one of the important characteristics of the qubit and which helps better understand the qubit life-time [5].

2.3.3. Ramsey Measurement (T_2^*)

In Ramsey Measurements we have similar setup as Rabi, here the qubit dephasing time is calculated, and also Ramsey measurements can be used to calculate the exact qubit frequency since the the qubit frequency we get from the spectroscopy is error prone. First the qubit is created in ground state and the then $\pi/2$-pulse is send to the qubit, after a time t another $\pi/2$-pulse is sent to qubit, then the qubit state is readout to know how much the qubit is shifted on the Bloch sphere [5].

2.4 Automating Spectroscopy and Rabi-Ramsey Measurements

We want a script that calculate all of the qubit characteristics mentioned above, and we can perform these measurements using the Labber GUI, but since this process consumes time it is ideal to have a script that performs these measurements and does the post-processing on the data obtained and store them in a data file.

In the automating script the Labber API for python is used to automate all the measurements and pipe-flow is created where a results obtained from one measurement are fed into the other since all these experiments are interlinked, which is observed the Fig[2.5]

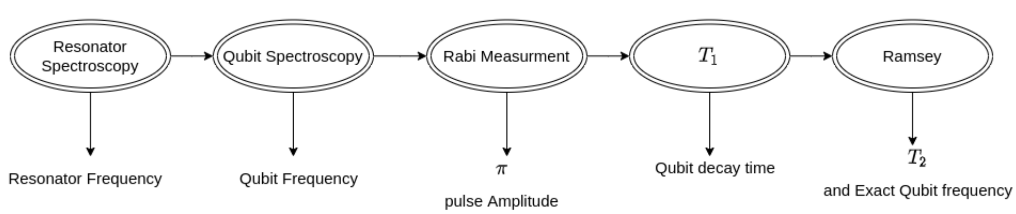


Figure 2.5: Flow chart

3 Results and Discussion

3.1 Mixer Calibration

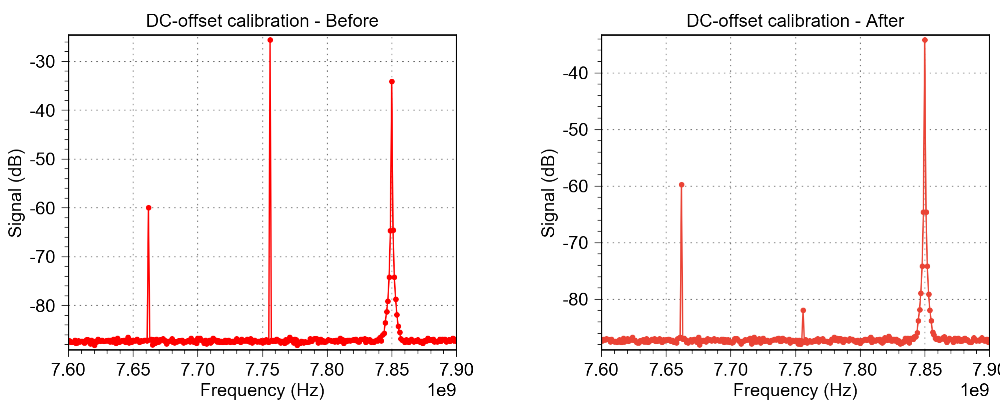
We were able to produce a Python script to automate the procedure for mixer calibration when supplied with an LO frequency and a desired frequency. The script operates by loading pre-configured Labber scenarios and then changing instrument channel values based on the supplied frequencies. It then schedules Labber to execute the desired scenarios, and extracts the relevant output from the Labber measurement. The script is able to execute on both Keysight and Vivace platforms, however sufficient testing on Vivace was not performed due to a lack of time.

3.1.1. DC-offset Calibration

The first task of mixer calibration is to minimize the LO signal leakage. This is done through the voltage offset procedure described in 2.1.3., and the script is able to do this consistently. The result of a DC-offset calibration performed by the script is shown in , and produces the optimal voltage offsets

$$v_1 = -37.611 \text{ mV}, v_2 = -18.3092 \text{ mV},$$

for the two different ports.



(a) Frequency spectrum of the IQ-mixer signal before minimizing LO leakage, with a dominant LO signal.

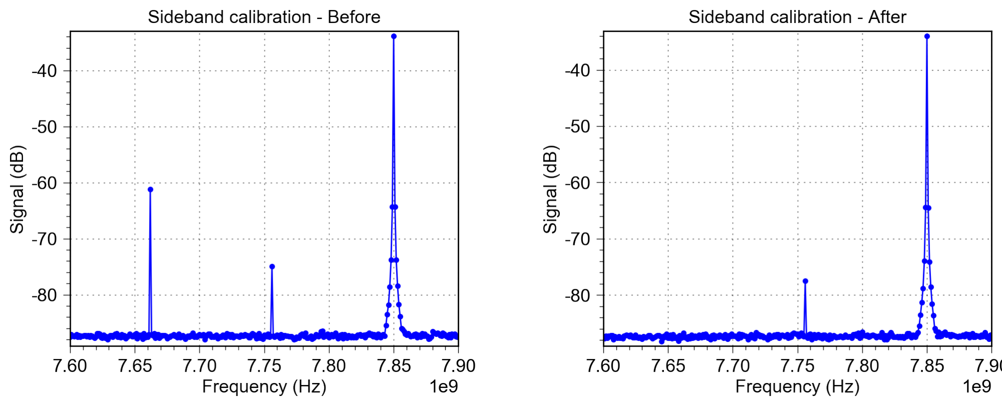
(b) Frequency spectrum of the IQ-mixer signal after minimizing LO leakage, with the LO signal greatly reduced.

Figure 3.1: Spectrum analyzer output from LO calibration, centered on the LO-frequency, in this case 7.756 GHz. To the left and right of the LO are the respective IF sidebands, with an intermediate frequency of 94 MHz. (a) shows the signal before any calibration has occured. (b) shows the signal after minimizing LO leakage.

Note that there is a large reduction in LO leakage. Before calibration, the LO leakage was the dominant signal, almost 10 dB larger than the desired sideband of 7.85 GHz. After performing the DC-offset calibration the LO signal is reduced to nearly -30 dB compared to the desired sideband. However, it is almost never possible to completely eliminate LO leakage.

3.1.2. Sideband Calibration

After minimizing the LO leakage the script automatically performs sideband calibration as described in 2.1.3. The results from such a calibration is shown in Figure 3.2. Note that it is possible to almost completely eliminate the undesired sideband. In this case the optimal calibration values is an amplitude scale of $982.88 \cdot 10^{-3}$ and a phase offset of $79.6301 \cdot 10^{-3}$ degrees.



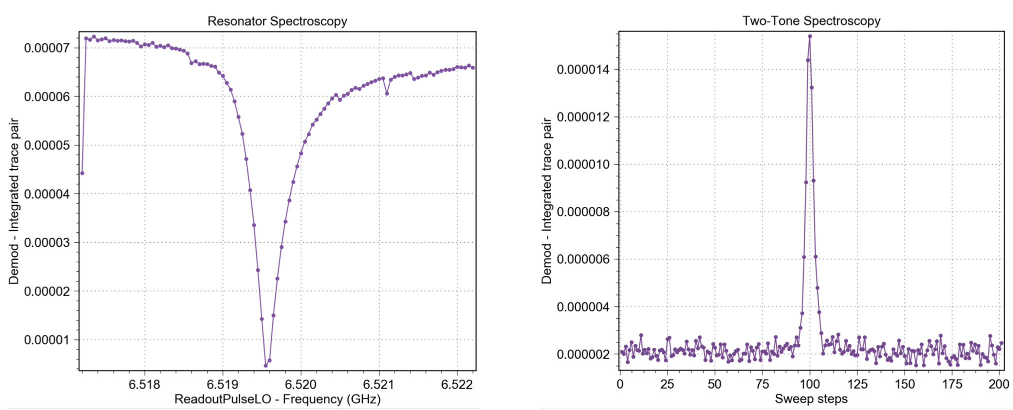
(a) Frequency spectrum of the IQ-mixer signal before minimizing the undesired sideband leakage.

(b) Frequency spectrum of the IQ-mixer signal after minimizing the undesired sideband leakage.

Figure 3.2: Spectrum analyzer output from sideband calibration, centered on the LO-frequency, in this case 7.756 GHz. To the left and right of the LO are the respective IF sidebands, with an intermediate frequency of 94 MHz. (a) shows the signal before any calibration has occured. (b) shows the signal after minimizing the sideband leakage.

3.2 Spectroscopy

When running the part of the script covering the spectroscopy we were able to produce two spectra, one for the resonator frequency and one for the qubit frequency both seen in figure 3.3. In the spectrum from the two-tone spectroscopy we were able to read a frequency of 100 steps, which was recalculated with equation 2.2.2. into 5.104 GHz. This value could then be used in the next step of the analysis.



(a) The spectrum produced by the resonator spectroscopy. The first point is likely remains from a previous measurement due to a bug in the software. The dip represents the frequency at which the resonator resonates.

(b) The spectrum produced by the two-tone spectroscopy. The peak arises at the qubit frequency in terms of steps and the signal is an average of the ground and the excited state.

Figure 3.3: Figure portraying the two spectra obtained from the spectroscopy part of the script.

3.3 Rabi-Ramsey

3.3.1. Rabi

To perform Rabi measurements, first we need to have qubit and resonant frequencies which are used to manipulate the qubit. When the script which is used to automate the Rabi measurements is run it performs the Rabi measurements and the fits the curve to the data obtained, this step is necessary for the calculation of the π pulse amplitude. The equation to which we curve fit the data is given is below.

$$A \sin(2\pi f T) \tag{1}$$

where A is the voltage and f is the frequency. The values we are interested is f this gives us the π-pulse amplitude that is need to excite the qubit from the ground state to excited state. In Fig[3.4] we can observe the Rabi plot which is attained after you curve fit the data.

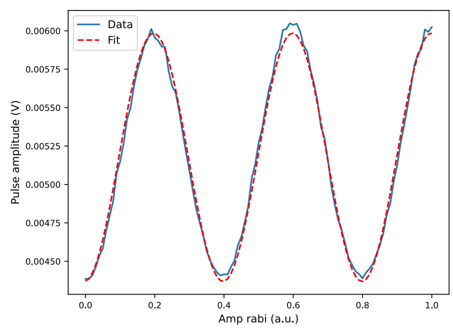


Figure 3.4: Rabi plot with curve fit, the π-pulse amplitude for the above case is 0.2 volts.

3.3.2. T_1

As previously mentioned T_1 calculates the Qubit decay time by manipulating the qubit state. In the Automated script this is done by preforming the measurements on qubit and curve fitting the data obtained, the data is fitted to following equation.

$$A \exp(\frac{-T}{T_1}) \tag{2}$$

where in the above equation T_1 corresponds to the decay time.

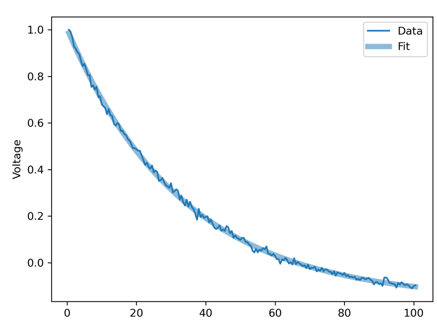


Figure 3.5: T1, the qubit decay time for the above case is 33 μs.

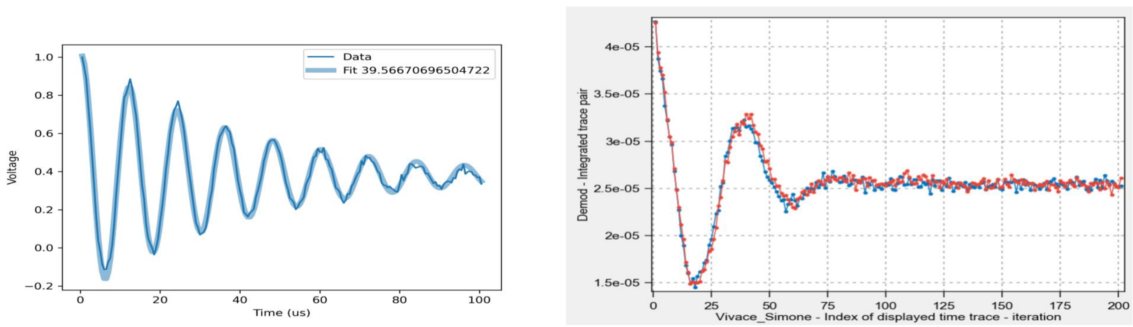
3.3.3. Ramsey (T_2^*)

The setup for the Ramsey measurement is similar to Rabi measurement, to automate the Ramsey measurement the scripts expects the resonant frequency, Qubit frequency and π- pulse amplitude.

After the measurements are preformed the data obtained is post-processed to find the information that is desired, the curve is fitted to the data obtained, the fitted curved is described as follows.

$$A \exp(\frac{-T}{T_2}) \cos 2\pi f T \tag{3}$$

where T_2 is the dephasing time, and the f is the error of the qubit frequency. If f $>$ 0, there is a need to find the exact frequency. But we are uncertain if the frequency is q + f or q - f, so the script performs the Ramsey measurement twice by changing the qubit frequency twice and if the f = 0 then the Ramsey measurement with f = 0, has the exact qubit frequency.



(a) Curve Fit of the Ramsey plot

(b) Ramsey plot

Figure 3.6: In the fig [a] after the curve fit we get the dephasing time (T_2^*) as 39.5666 μs for this case.

4 Conclusion and Outlook

The work done in this project can used to decrease the time consumed during the routine measurements, and this work can be improved upon on the user friendliness and adaptability of the code. The results achieved after implementation of the automating script correspond closely with the measurements run with Labber GUI, but there is still room for the improvement. Currently, the code still expects many inputs from the user, which can likely be reduced through further development. There is still work to do for coupling the different aspects of qubit tuneup, since mixer calibration and the qubit tuneup currently are different scripts and does not interact currently.

There is also potential for greater automation, for example by performing mixer calibration for multiple frequencies in succession to avoid having to recalibrate the mixers quite so often, and tuning multiple qubits by interacting with a switch instrument to measure several qubits without human intervention. There is also work left to do for the scripts to run on both the Keysight and Vivace platforms, as parts of the implementation has not been tested on both.

References

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